

Wound-Field Synchronous Machine-System Integration toward Increased Power Density and Commercialization



Presenters:

Dr. Lakshmi Varaha Iyer, Magna International

Prof. Ian Brown, Illinois Institute of Technology

Prof. Dan Ludois, University of Wisconsin-Madison

Overview

Timeline

Start Date: October 2019

End Date: December 2022

Budget

Total Project Funding: \$ 870,000

- DOE: \$ 700,000
- Participants: \$ 170,000

Actual Costs Incurred: \$ 64,448

- DOE: \$ 51,558
- Participants: \$ 12,890

Status: 15% of time expended vs 9% of budget

Actual costs incurred do not reflect IIT& UW costs which have been incurred but have not yet submitted to DOE for reimbursement.

Barriers & Technical Targets

- Develop 125kW wound field synchronous motor (WFSM) demonstrating:
 - 8X increase in power density
 - Cost \leq \$ 3.3/kW

Accomplishments

- All Subcontracts & IP Agreements are in place
- Pareto maps generated for different motor designs through electromagnetic simulations
- Baseline case generated for stator cooling jacket through CFD analysis
- Architecture of rotor electronics established through simulations

Technology Partners

Magna International, Inc. (Magna)

Illinois Institute of Technology (IIT)

University of Wisconsin – Madison (UW)

Project Objectives

The objective of the project is to develop **125kW wound field synchronous electric traction motor**, demonstrating an **8X increase in power density** and **cost $\leq \$ 3.3/\text{kW}$** , as defined in the EDT Research Consortium Strategic Goal.

MAGNA

Principal Investigator – Dr. Lakshmi Varaha Iyer

- Motor Cooling
- Design for Manufacturing
- Prototyping and Testing

Project Management and Reporting – Tim Skszek

Compliance – Shameeka Ward

Invoicing – Bucciero & Associates PC (contractor)

University of Wisconsin-Madison

Co-principal Investigator – Prof. Dan Ludois

- Rotor Excitation

Illinois Institute of Technology

Co-principal Investigator – Prof. Ian Brown

- WFSM Design

Deliverables:

Dec. 2020 Preliminary FEA results demonstrating potential of meeting program objectives

Dec. 2021 Completion of motor design for manufacturing

Dec. 2022 Prototype motors tested by Magna and delivered to DOE

Project Approach

Budget Period 1: October 2019 – December 2020

Research, Engineering and Concept Design Phase

Task 1.1 – Design and development of efficient stator and rotor cooling systems

Subtask 1.1.1 – Investigation of novel stator and rotor cooling systems

Subtask 1.1.2 – Comparative analysis of cooling systems

Task 1.2 – Electromagnetic and structural design of the wound field synchronous machine

Subtask 1.2.1 – Development of magneto-structural WFSM design optimization tools

Subtask 1.2.2 – Initial high-power density WFSM electromagnetic and structural design

Task 1.3 – Design and development of rotor power transfer system

Subtask 1.3.1 – Design of the MHz frequency wireless power transfer inverter

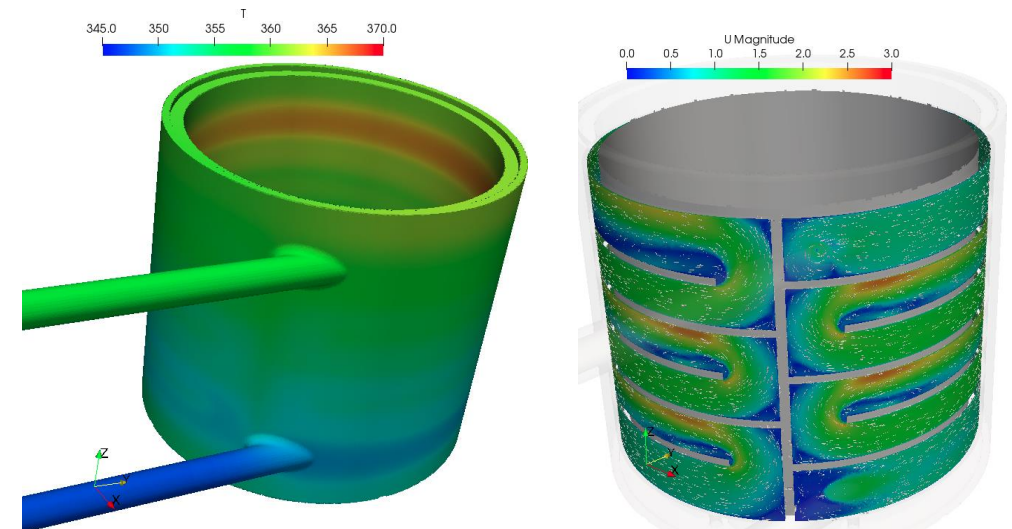
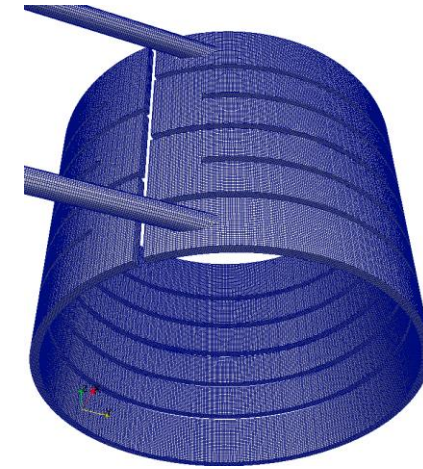
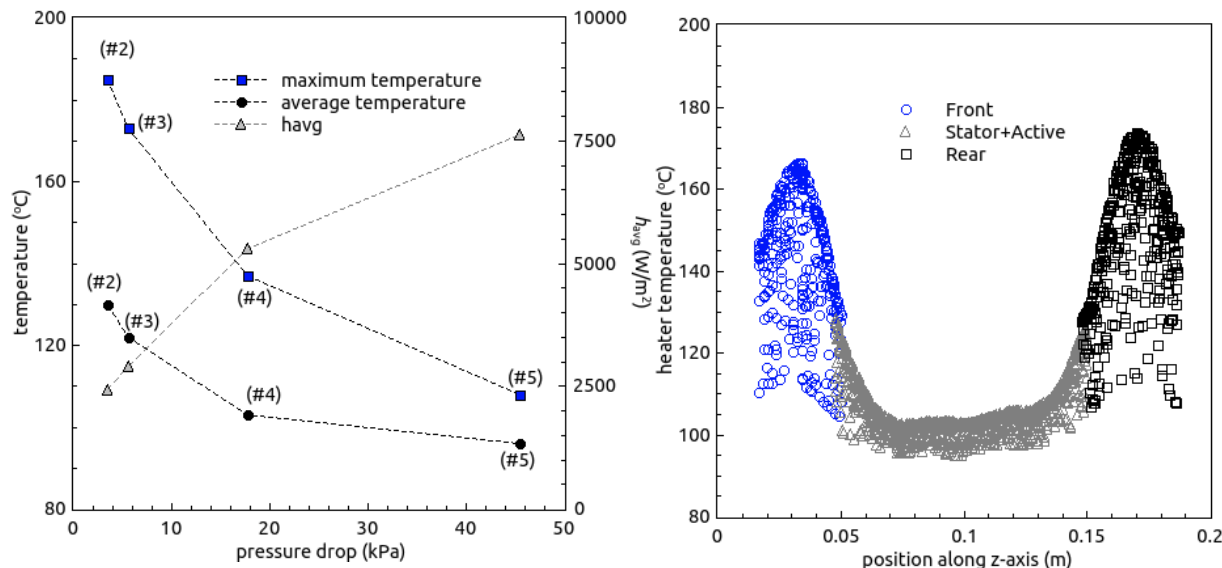
Subtask 1.3.2 – Design of the rotating rectifier board with integrated coupling structure

Go/No Go	Finite element analysis confirms that initial WFSM design has ≥ 50 kW/L power density and cost $\leq \\$3.3/\text{kW}$
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Motor Cooling Design & Analysis

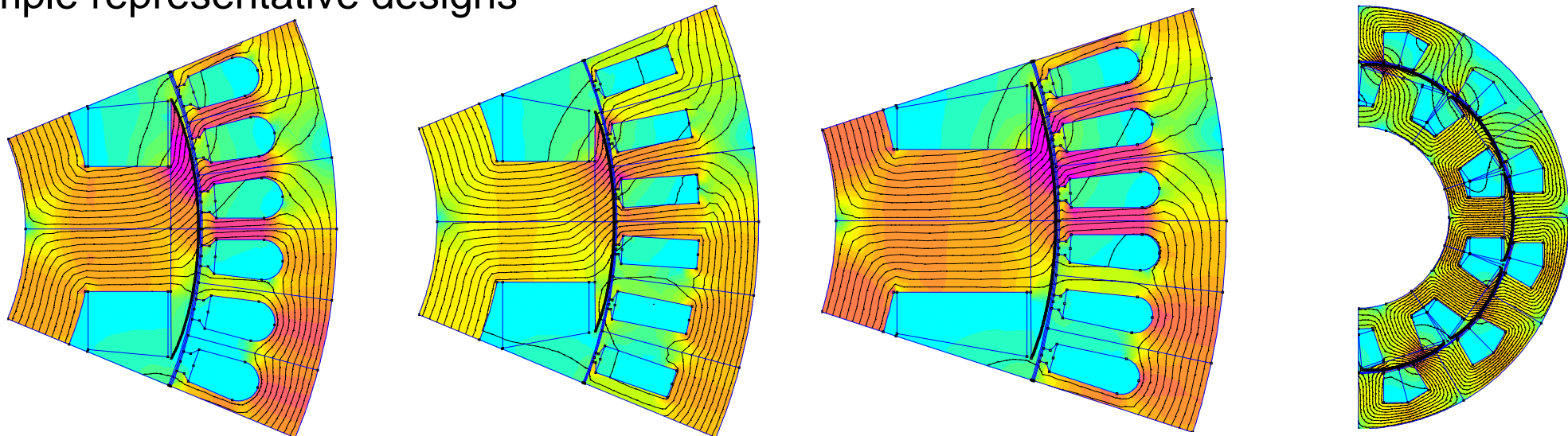
Established package dimensions of the motor and stator jacket based on the design parameters listed below:

- Flow rate: 4 – 10L/min
- Coolant type: 50/50 Water/Glycol
- Coolant inlet temperature: 65 – 85 deg C
- Geometry and meshing for CFD analysis setup for baseline case
- Flow path and velocities, verified
- Temperatures in the solid region, verified
- Optimization of stator jacket design, ongoing



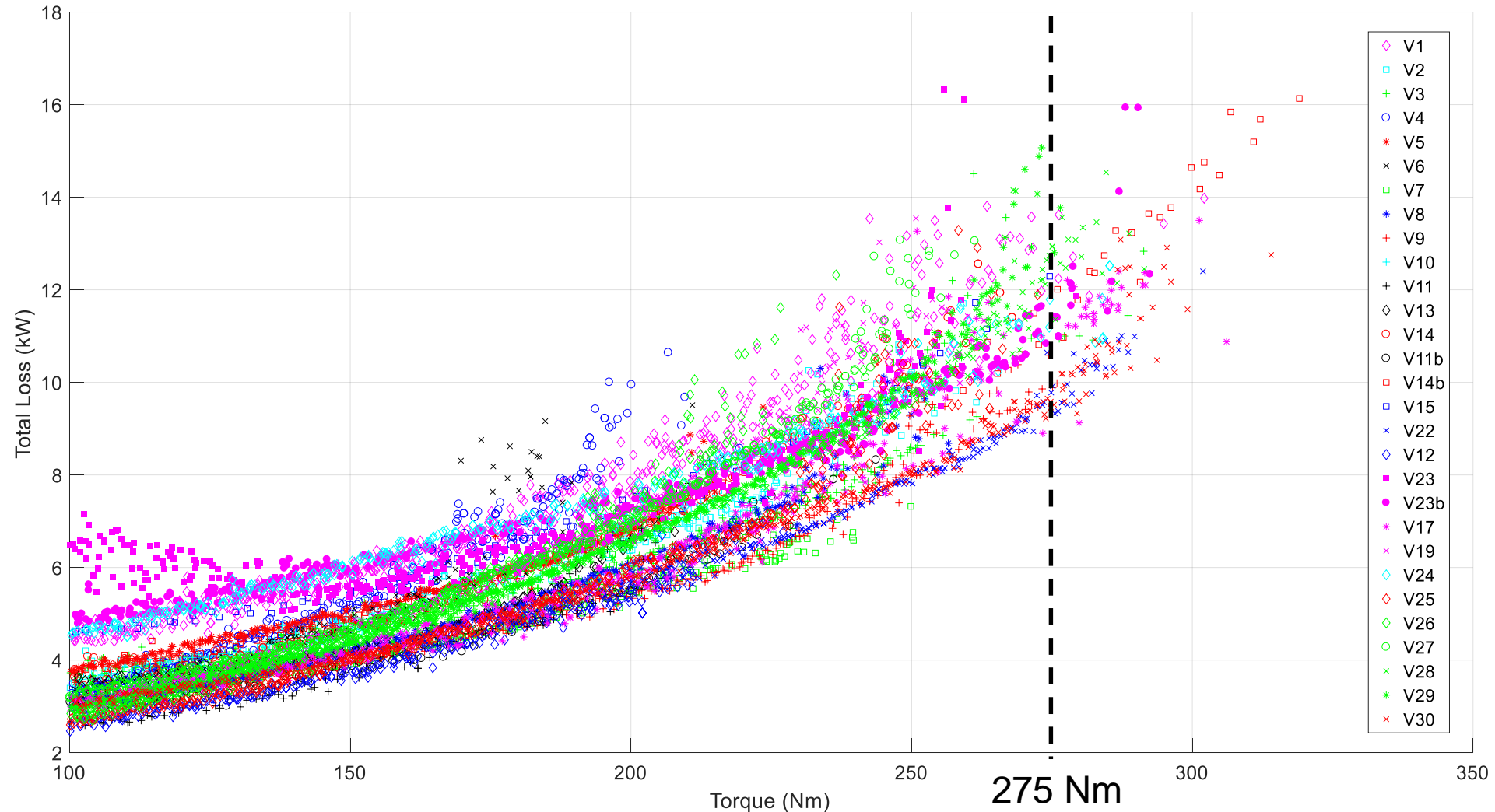
Motor Design Optimization, Wound Field Synchronous Machine (WFSM)

- IIT developed a WFSM design tool for large scale evolutionary optimization to determine Pareto fronts.
- Conducted multi-objective optimization to maximize the electromagnetic torque and minimize the machine losses subject to constraints.
- Examined many distributed/fractional slot concentrated winding slot pole configurations and winding technologies including ~15 stator and rotor geometric variables.
 - The number of designs evaluated during optimization runs up to 48,000 designs
- Example representative designs



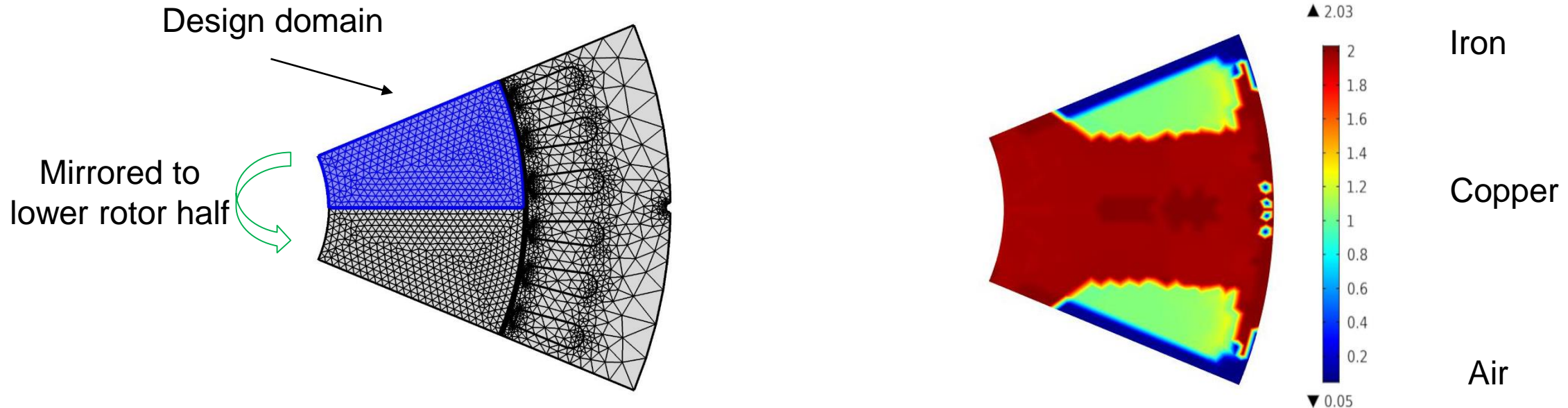
Summary of Optimization Pareto Fronts

- Target peak torque is ~275 Nm; many designs meet the target torque requirements



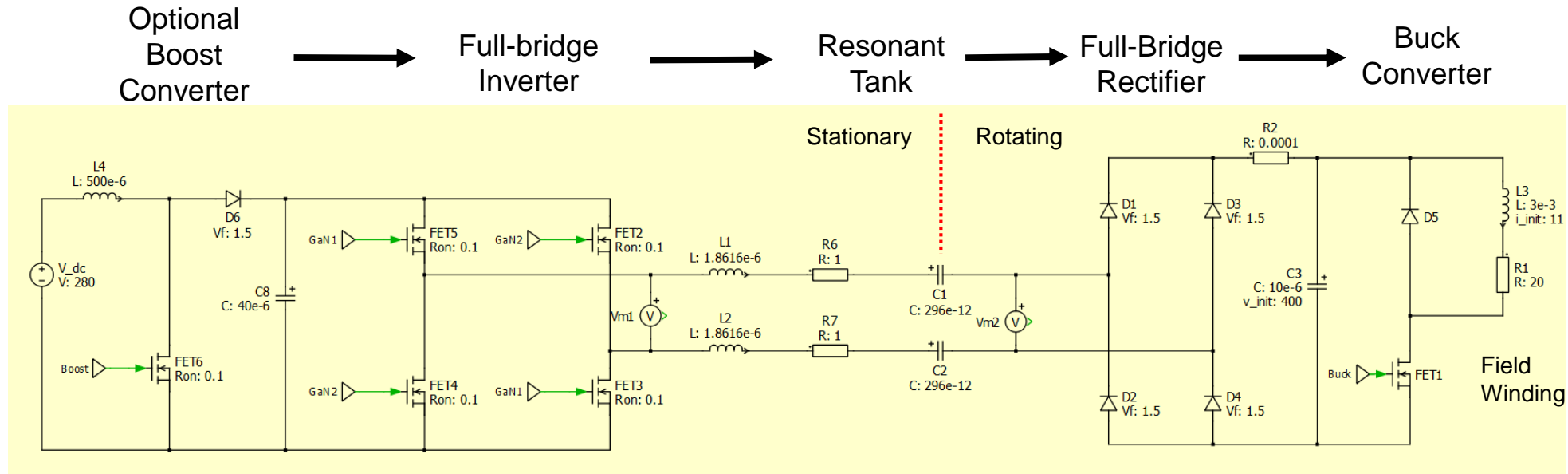
Optimized WFSM rotor design using an additional multi-material magneto-structural tool

- Copper, electrical steel, or air distributed in the rotor design domain in a free-form manner
- Density based solid isotropic with material penalization (SIMP) approach used
- Presently requires a predefined stator; used in conjunction with large scale design optimizations
- Example magneto-structural WFSM rotor topology optimization from the tool to maximize torque and minimize rotor losses subject to torque ripple, stress, and compliance constraints



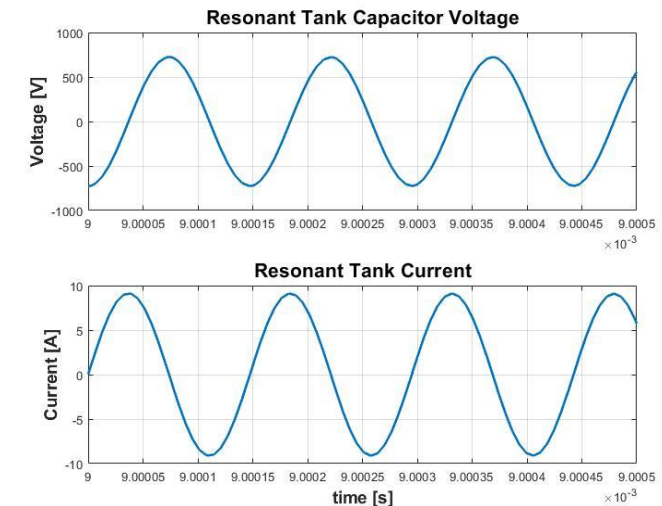
Project Accomplishments & Progress

Capacitive Power Coupling Circuit Diagram



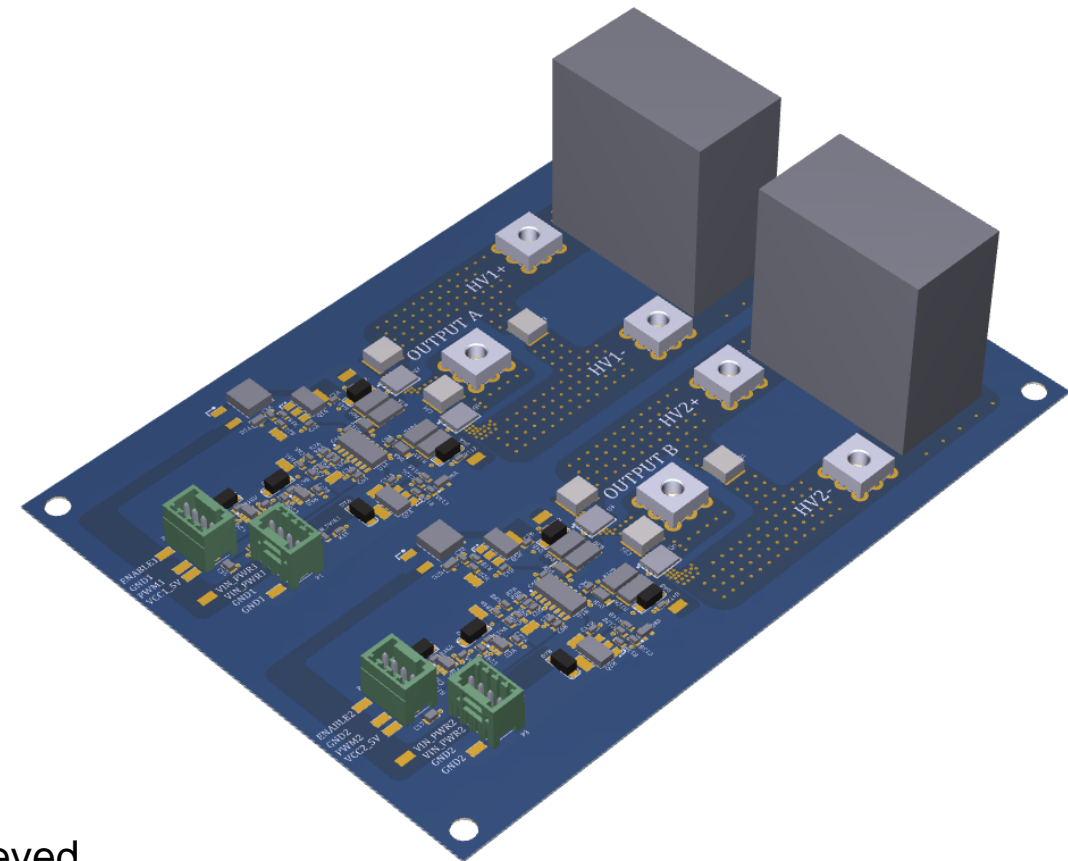
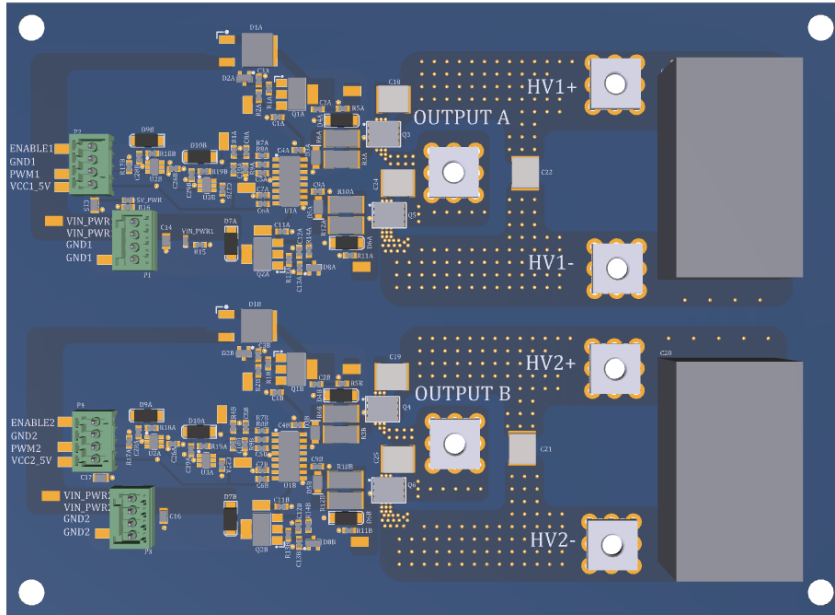
Overall Design Parameters

- Output power to field = 2.5 kW
- Frequency = 6.78 MHz
- Field resistance = 20 Ω
- Inverter bus voltage = 400 V (optional boost can support lower battery voltage)
- RMS Inverter / Tank Phase Current: 7 A
- Field Current: 11.2 A
- Efficiency: ~90%



Project Accomplishments & Progress

Initial rendering of 6.78 MHz Rotor Inverter

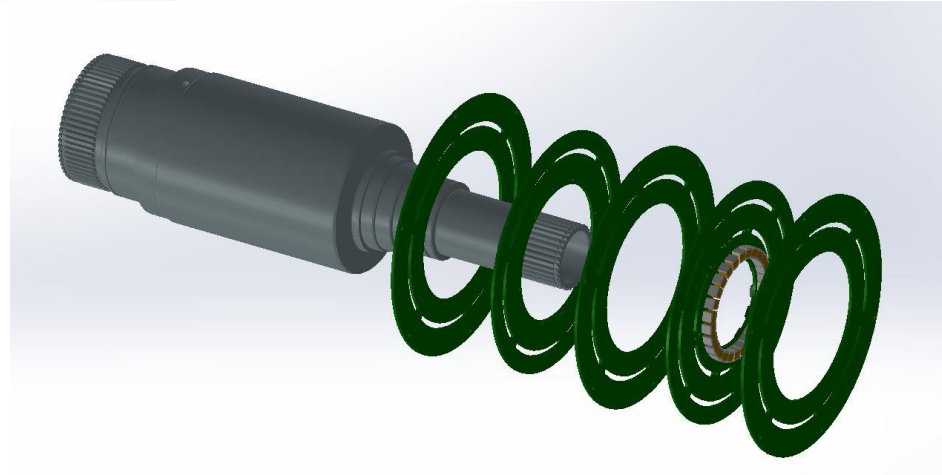
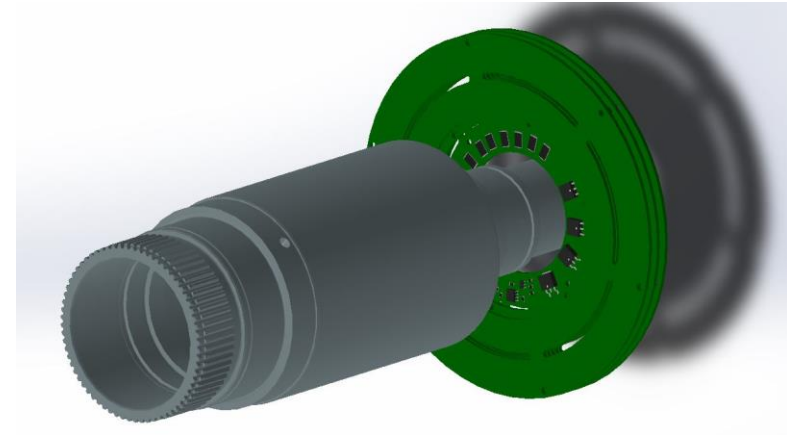
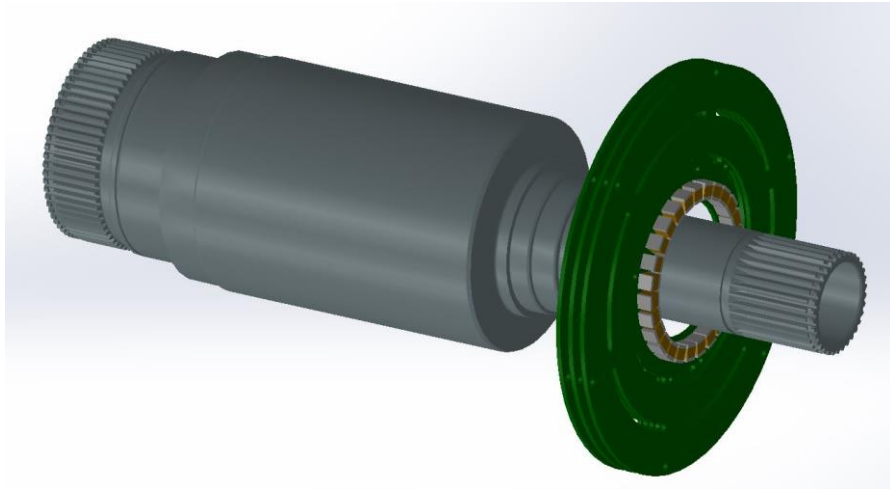


Notes

- Initial Design using Altium
- GaN FETs from GaN Systems
- 4" x 6" footprint for prototype design
- Size reduction anticipated after desired performance achieved.

Project Accomplishments & Progress

Images of CPC Stack on WFSM Shaft



Team Collaboration & Coordination

Dr. Lakshmi Varaha Iyer of Magna International leads the technical team comprised of; Prof. Ian Brown, Illinois Institute of Technology and Prof. Dan Ludois, University of Wisconsin-Madison.

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| • DOE Project Kickoff Meeting | October 2109 |
| • Semi-annual Face/Face Project Meeting | November 2019 |
| • WebEx Project Meetings | Ongoing, Weekly Meetings |

Tim Skszek of Magna International leads the Subcontracts, IP, financial reporting and compliance team comprised of; Robert Lapointe, Illinois Institute of Technology, Dawn Herrick, UW-Madison, Emily Bauer & Michael Carey, Wisconsin Alumni Research Foundation, Jay Paranjpe & Shameka Ward, Magna International.

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|--------------------------------------|----------------------------|
| • UW Subcontract and IP Agreements | January 2020 |
| • IIT Subcontract and IP Agreements | February 2020 |
| • Financial Reporting and Compliance | Ongoing, Quarterly Reports |

Market Impact and Sustainability

- An 8x increase in power density provides significant weight and packaging benefits to the powertrain leading to increased EV driving range.
- The use of copper for windings and steel for laminations enable significant cost reduction of the motor active material.
- Through the removal of rare earth permanent magnets, reduced concerns over environmental footprint and commercial availability.
- High power factor through field excitation control reducing the required size of the main traction inverter.
- Direct field weakening and large constant power speed range (CPSR) through field excitation control.
- Potential for improved safety through field control during inverter fault conditions

Efficient use of Financial Resources

- Successful execution of a small \$870,000 project, conducted over a 39-month project period by three recipients demands the efficient use of resources and execution according to the project plan.
- The opportunity to leverage the results of the past VTO-funded WFSM research effort, as well as the research team from IIT and UW-Madison significantly increases efficiency.
- Weekly project meetings are conducted via WebEx maintaining the project focus relative to near- and long-term objectives, as well as a forum to present and address open issues in a timely manner.

Thank You

